

Exhibit B



US007525408B1

(12) **United States Patent**
Li et al.

(10) **Patent No.:** **US 7,525,408 B1**
(45) **Date of Patent:** **Apr. 28, 2009**

(54) **METHOD FOR MAKING MAGNETIC COMPONENTS WITH N-PHASE COUPLING, AND RELATED INDUCTOR STRUCTURES**

(75) Inventors: **Jieli Li**, Albany, CA (US); **Charles R. Sullivan**, West Lebanon, NH (US); **Angel Gentchev**, Fremont, CA (US)

(73) Assignee: **Volterra Semiconductor Corporation**, Fremont, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 130 days.

5,225,971 A	7/1993	Spreen	
5,436,818 A	7/1995	Barthold	
5,565,837 A *	10/1996	Godek et al.	336/232
5,568,111 A	10/1996	Metsler	
5,594,402 A *	1/1997	Krichtafovich et al.	336/65
5,764,500 A	6/1998	Matos	
5,939,966 A	8/1999	Shin' Ei	
6,018,468 A	1/2000	Archer et al.	
6,060,977 A	5/2000	Yamamoto et al.	
6,348,848 B1	2/2002	Herbert	

(Continued)

(21) Appl. No.: **11/852,226**

OTHER PUBLICATIONS

(22) Filed: **Sep. 7, 2007**

Wong, Pit-Leong, et al.; A Novel Modeling Concept for Multi-coupling Core Structures; Center for Power Electronics Systems; IEEE.

Related U.S. Application Data

(Continued)

(62) Division of application No. 10/318,896, filed on Dec. 13, 2002, now Pat. No. 7,352,269.

Primary Examiner—Tuyen T. Nguyen

(74) *Attorney, Agent, or Firm*—Lathrop & Gage LLP

(51) **Int. Cl.**
H01F 5/00 (2006.01)

(57) **ABSTRACT**

(52) **U.S. Cl.** **336/200**

(58) **Field of Classification Search** 336/65,
336/83, 183, 200, 220–222, 232
See application file for complete search history.

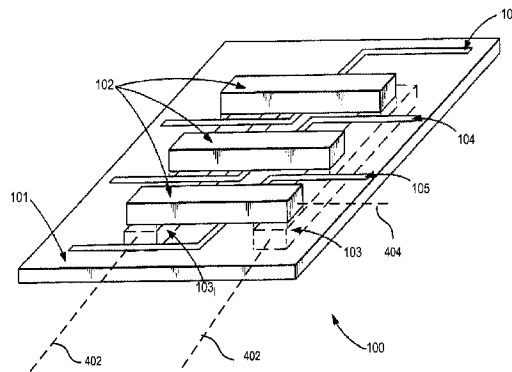
Methods and structures for constructing a magnetic core of a coupled inductor. The method provides for constructing N-phase coupled inductors as both single and scalable magnetic structures, where N is an integer greater than 1. The method additionally describes how such a construction of the magnetic core may enhance the benefits of using the scalable N-phase coupled inductor. The first and second magnetic cores may be formed into shapes that, when coupled together, may form a single scalable magnetic core. For example, the cores can be fashioned into shapes such as a U, an I, an H, a ring, a rectangle, and a comb, that cooperatively form the single magnetic core.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,212,543 A	8/1940	Jovy
3,878,495 A	4/1975	Thomas
4,488,136 A	12/1984	Hansen et al.
4,777,406 A	10/1988	Ross et al.
4,800,479 A	1/1989	Bupp
5,003,277 A	3/1991	Sokai et al.
5,177,460 A	1/1993	Dhyanchand et al.
5,182,535 A	1/1993	Dhyanchand
5,204,809 A	4/1993	Andresen

20 Claims, 13 Drawing Sheets



US 7,525,408 B1

Page 2

U.S. PATENT DOCUMENTS

6,356,179	B1	3/2002	Yamada	
6,362,986	B1	3/2002	Schultz et al.	
6,377,155	B1	4/2002	Allen et al.	
6,438,818	B1	8/2002	Costa	
6,549,111	B1	4/2003	De Graaf et al.	
6,737,951	B1	5/2004	Decristofaro et al.	
7,187,263	B2 *	3/2007	Vinciarelli	336/200
7,280,025	B2	10/2007	Sano	
7,352,269	B2	4/2008	Li et al.	

OTHER PUBLICATIONS

Wong, Pit-Leong, et al.; Performance Improvements of Interleaving VRMs With Coupling Inductors, IEEE Transactions on Power Electronics; vol. 16, No. 4; pp. 499-507; Jul. 2001.

Cooper Bussmann, "Product Data Sheet for Low Profile Inductor (Surface Mount)" retrieved from <http://www.angliac.com>, May 2003.

Xu, J., et al; Analysis by Finite Element Method of a Coupled Inductor Circuit Used as Current Injection Interface; IEEE; pp. 147-151; 1996.

Pulse, SMT Power Inductors Power Beads—PA0766NL Series; pp. 53-55; date unknown. Applicants do not concede this reference as prior art.

Vitec, Dual High Frequency High Power Inductor, AF4390A data sheet; date unknown. Applicants do not concede this reference as prior art.

Wong, Pit-Leong, et al., "Investigating Coupling Inductors in the Interviewing" Applied Power Electronics Conference and Exposition, 2000. APEC 2000. Fifteenth Annual IEEE; Mar. 2000; pp. 973-978.

U.S. Appl. No. 10/318,896, Office Action mailed Jun. 15, 2004, pp. 1-5.

U.S. Appl. No. 10/318,896, Response to Office Action mailed Jun. 15, 2004; filed Aug. 16, 2004; 20 pages.

U.S. Appl. No. 10/318,896, Office Action mailed Dec. 6, 2004, pp. 1-4.

U.S. Appl. No. 10/318,896, Response to Office Action mailed Dec. 6, 2004; filed Feb. 7, 2005; 17 pages.

U.S. Appl. No. 10/318,896, Office Action mailed Dec. 2, 2005, 7 pages.

U.S. Appl. No. 10/318,896, Response to Office Action mailed Jun. 14, 2005; filed Sep. 14, 2005; 33 pages.

U.S. Appl. No. 10/318,896, Office Action mailed Jun. 14, 2005, pages.

U.S. Appl. No. 10/318,896, Response to Office Action mailed Dec. 2, 2005; filed Mar. 24, 2006; 27 pages.

U.S. Appl. No. 10/318,896, Office Action mailed Jun. 30, 2006, pp. 1-6.

U.S. Appl. No. 10/318,896, Petition to Review Restriction Requirement filed Aug. 24, 2006.

U.S. Appl. No. 10/318,896, Response to Office Action mailed Jun. 30, 2006; filed Oct. 25, 2006.

U.S. Appl. No. 10/318,896, Office Action mailed Jan. 18, 2007; 8 pages.

U.S. Appl. No. 10/318,896, Statement of the Substance of Interview; filed Apr. 23, 2007; pp. 1-2.

U.S. Appl. No. 10/318,896, Response to Office Action mailed Jan. 18, 2007 and RCE; filed Jul. 18, 2007; 46 pages.

Papers received from Santangelo Law Office dated Dec. 22, 2006 and May 30, 2007.

U.S. Appl. No. 11/852,207, Restriction Requirement mailed Feb. 26, 2008.

U.S. Appl. No. 11/852,207, Response to Restriction Requirement filed Mar. 26, 2008.

U.S. Appl. No. 11/852,231, Restriction Requirement mailed Feb. 26, 2008.

U.S. Appl. No. 11/852,231, Response to Restriction Requirement filed Mar. 26, 2008.

U.S. Appl. No. 11/852,216, Restriction Requirement mailed Feb. 26, 2008.

U.S. Appl. No. 11/852,216, Response to Restriction Requirement filed Mar. 26, 2008.

U.S. Appl. No. 10/318,896, Supplemental Amendment filed Sep. 14, 2007.

U.S. Appl. No. 10/318,896; Statement of the Substance of Interview, Sep. 27, 2007.

U.S. Appl. No. 10/318,896; Notice of Allowance, Oct. 4, 2007.

U.S. Appl. No. 10/318,896, Supplemental Notice of Allowance, Dec. 13, 2007.

U.S. Appl. No. 10/318,896, Issue Fee Payment, Jan. 4, 2008.

U.S. Appl. No. 10/318,896, Sixth Request for Acknowledgement of an Information Disclosure Statement, Jan. 4, 2008.

U.S. Appl. No. 11/852,216 Notice of non-compliant amendment mailed Jul. 7, 2008; 3 pages.

U.S. Appl. No. 11/852,207, Office Action mailed Jun. 20, 2008, 7 pages.

U.S. Appl. No. 11/852,216 Response to Restriction Requirement filed Sep. 4, 2008; 3 pages.

U.S. Appl. No. 11/852,231, Applicant Interview Summary, Aug. 29, 2008; 2 pages.

U.S. Appl. No. 11/852,231, Notice of Non-Compliant Amendment mailed Jul. 2, 2008; 3 pages.

U.S. Appl. No. 11/852,231, Response to Restriction Requirement, filed Sep. 2, 2008; 3 pages.

U.S. Appl. No. 11/852,231, Examiner Interview Summary mailed Aug. 6, 2008; 2 pages.

U.S. Appl. No. 11/929,827, Notice of Allowance mailed Oct. 21, 2008; 7 pages.

U.S. Appl. No. 11/929,827, Restriction Requirement mailed Aug. 18, 2008; 7 pages.

U.S. Appl. No. 11/929,827, Response to Restriction Requirement filed Sep. 4, 2008; 3 pages.

* cited by examiner

U.S. Patent

Apr. 28, 2009

Sheet 1 of 13

US 7,525,408 B1

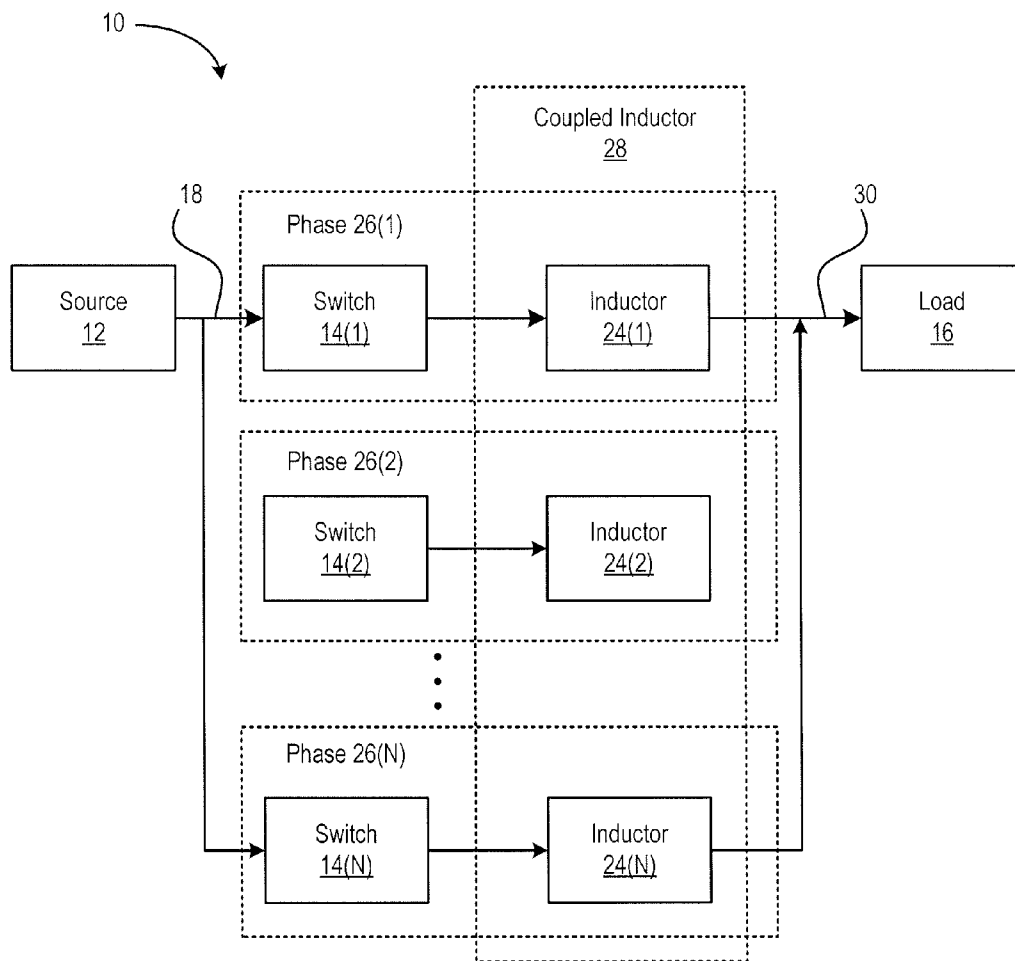


FIG. 1

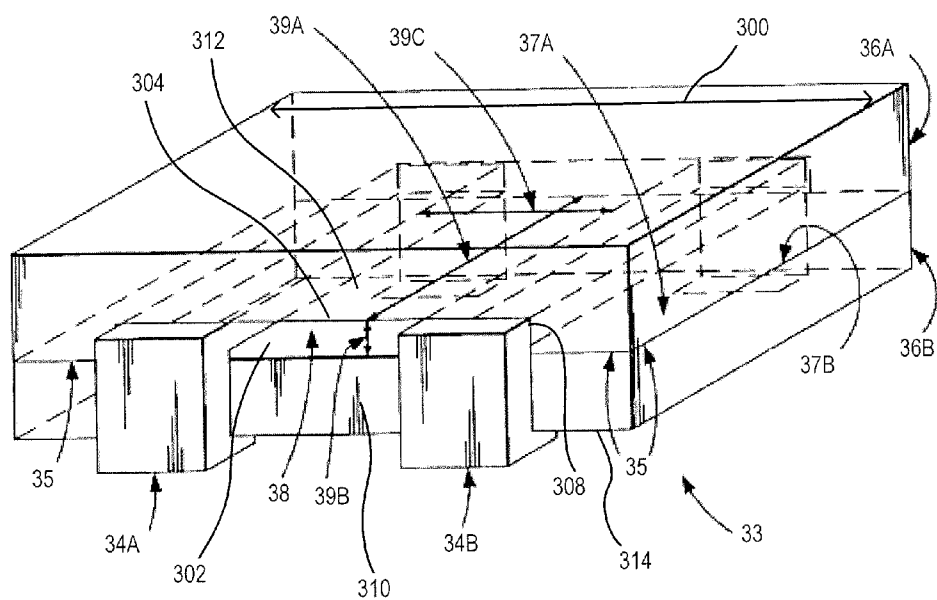


FIG. 2

U.S. Patent

Apr. 28, 2009

Sheet 3 of 13

US 7,525,408 B1

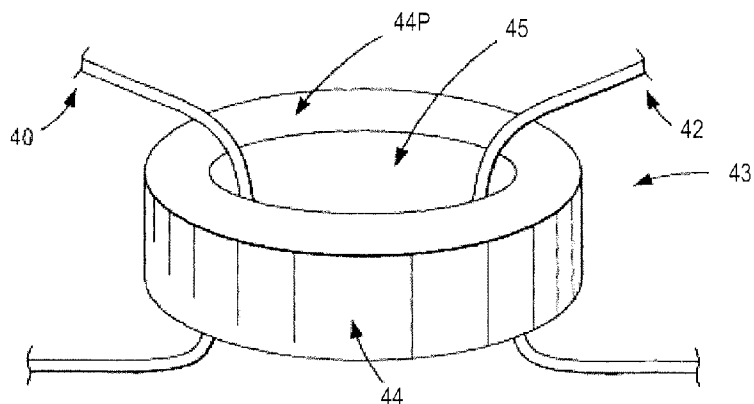


FIG. 3

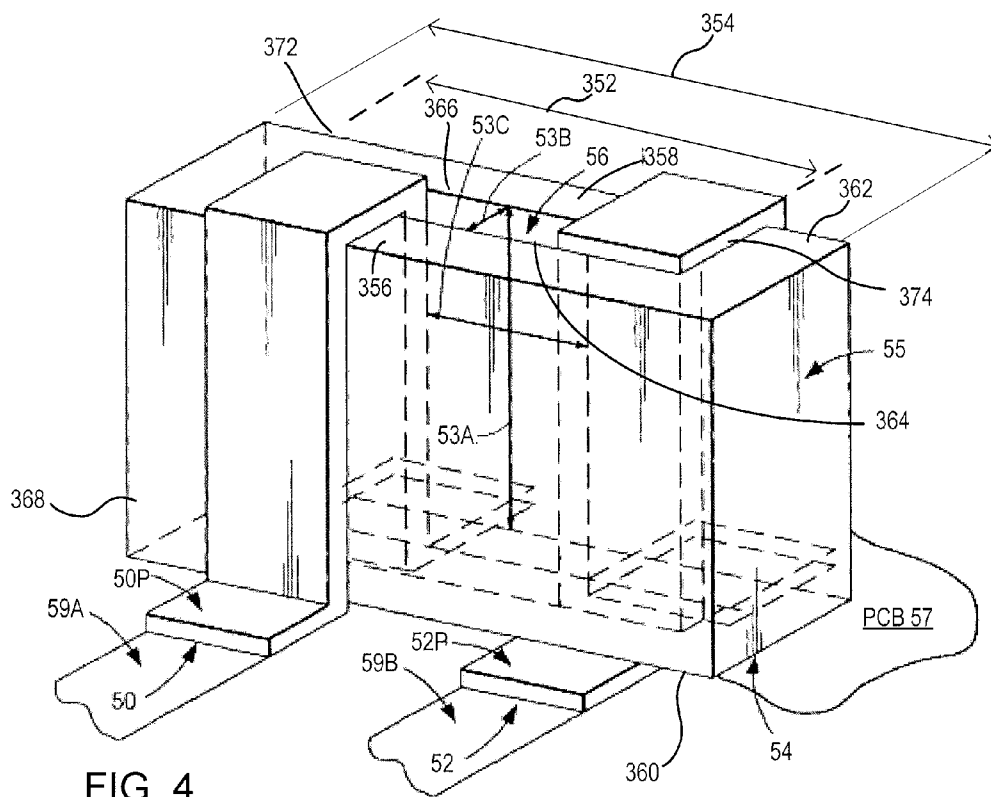


FIG. 4

U.S. Patent

Apr. 28, 2009

Sheet 4 of 13

US 7,525,408 B1

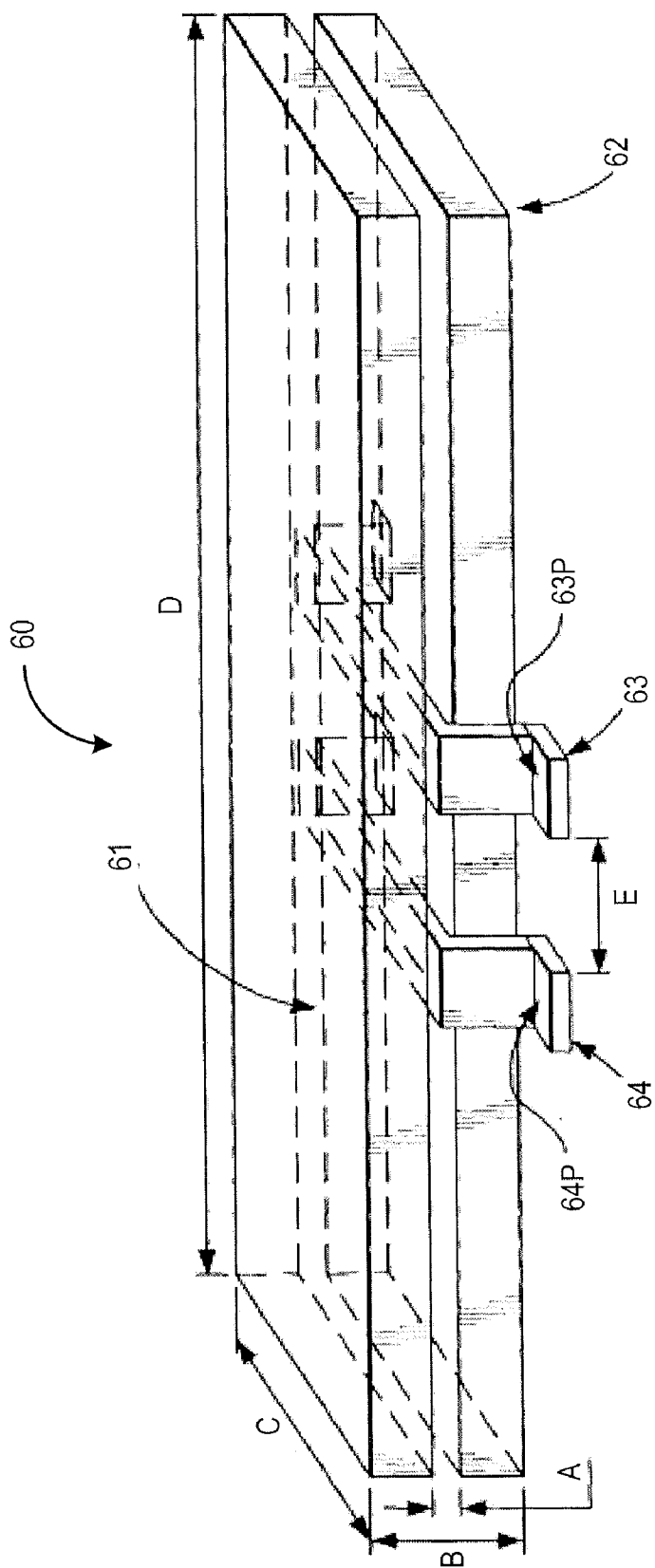


FIG. 5

U.S. Patent

Apr. 28, 2009

Sheet 5 of 13

US 7,525,408 B1

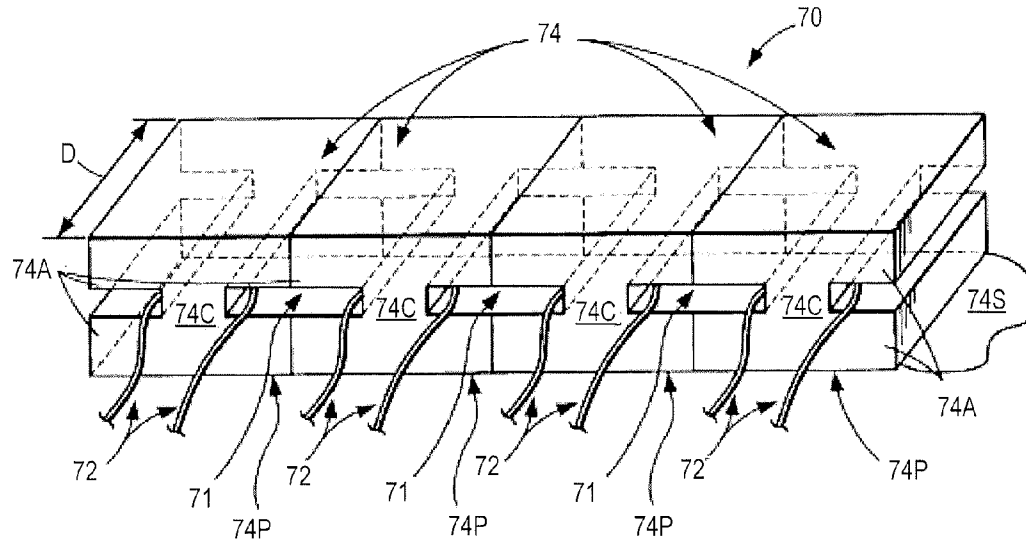


FIG. 6

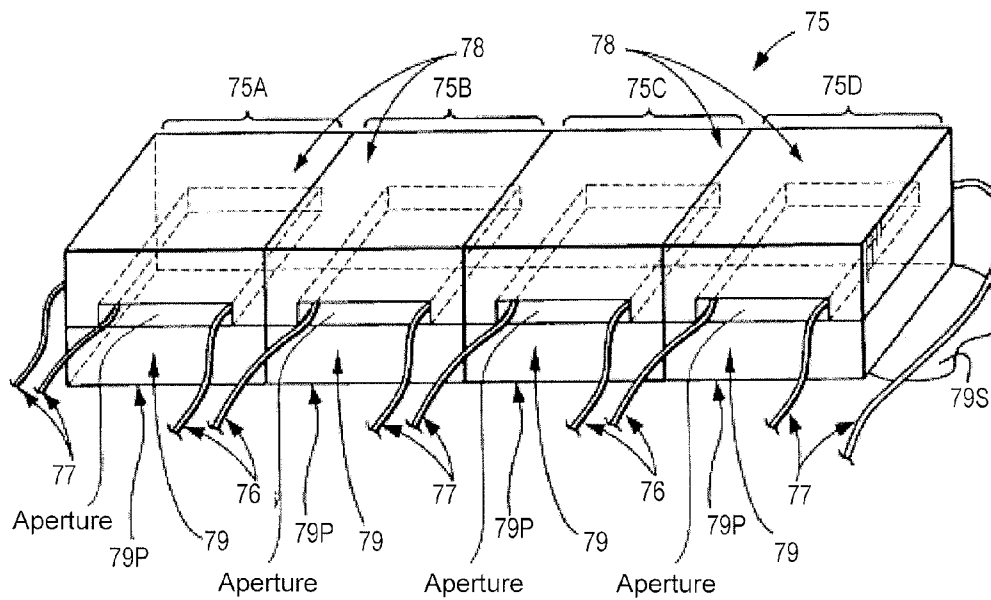
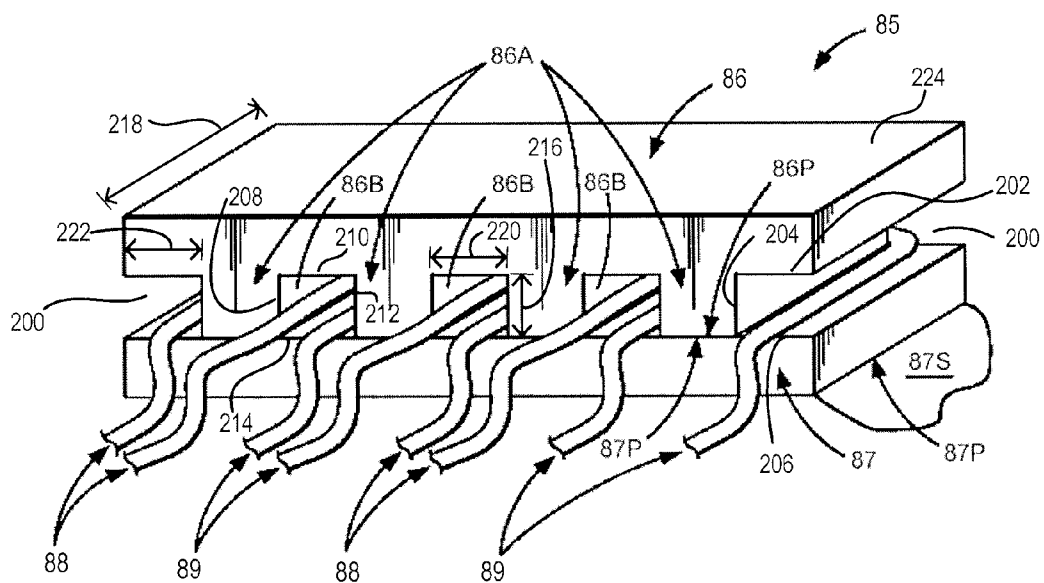
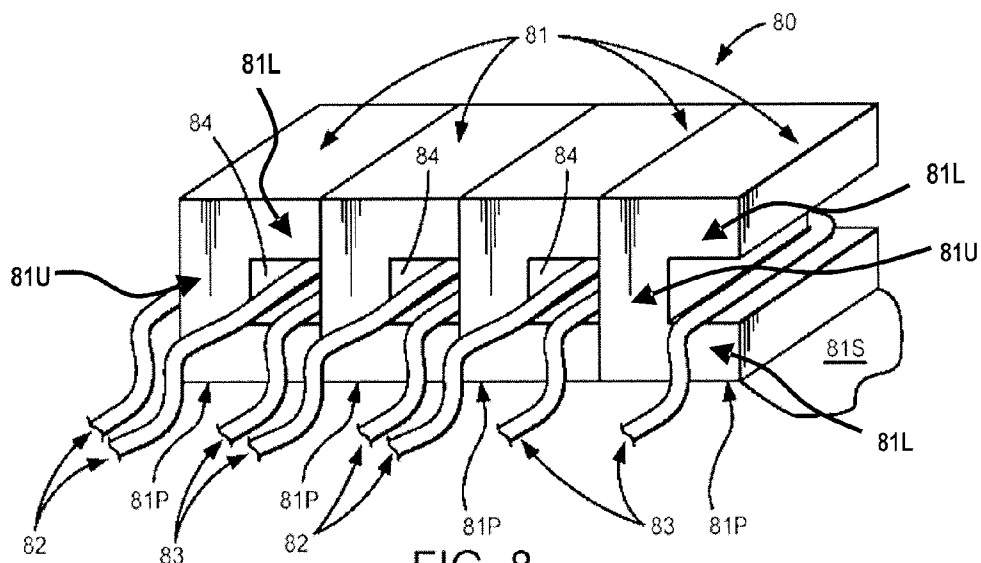


FIG. 7



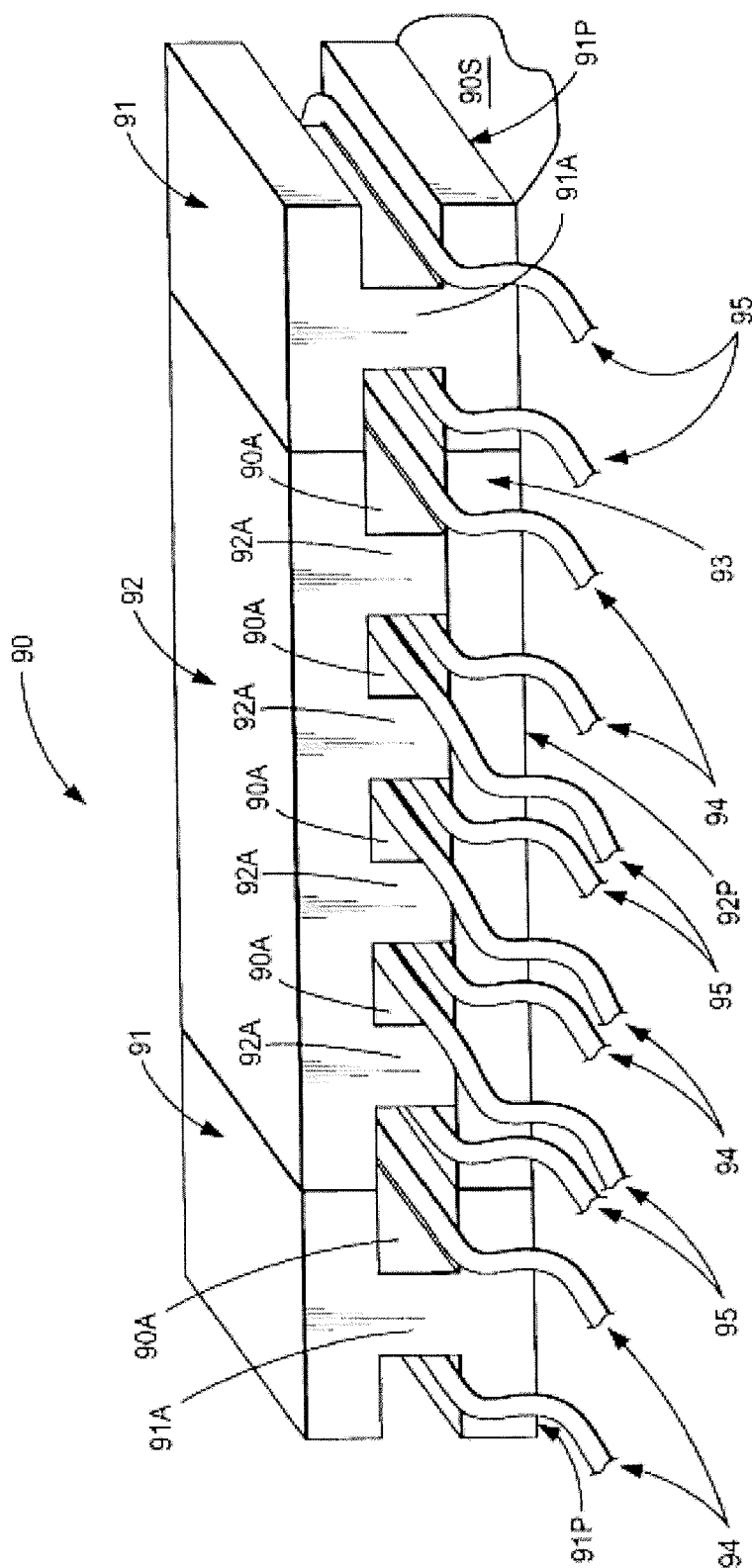


FIG. 10

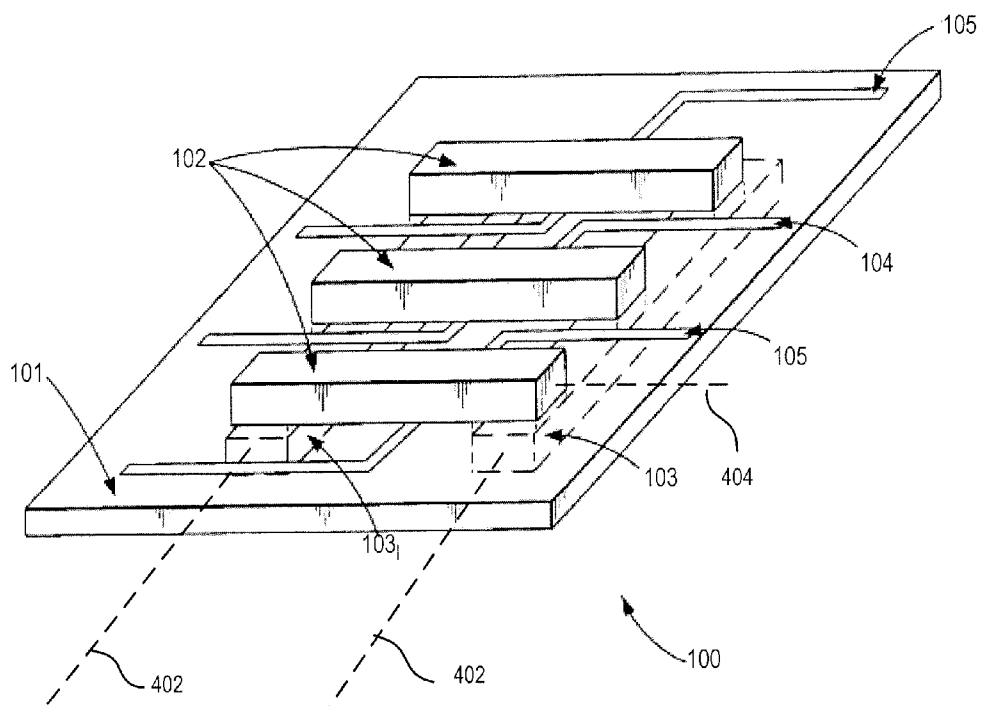


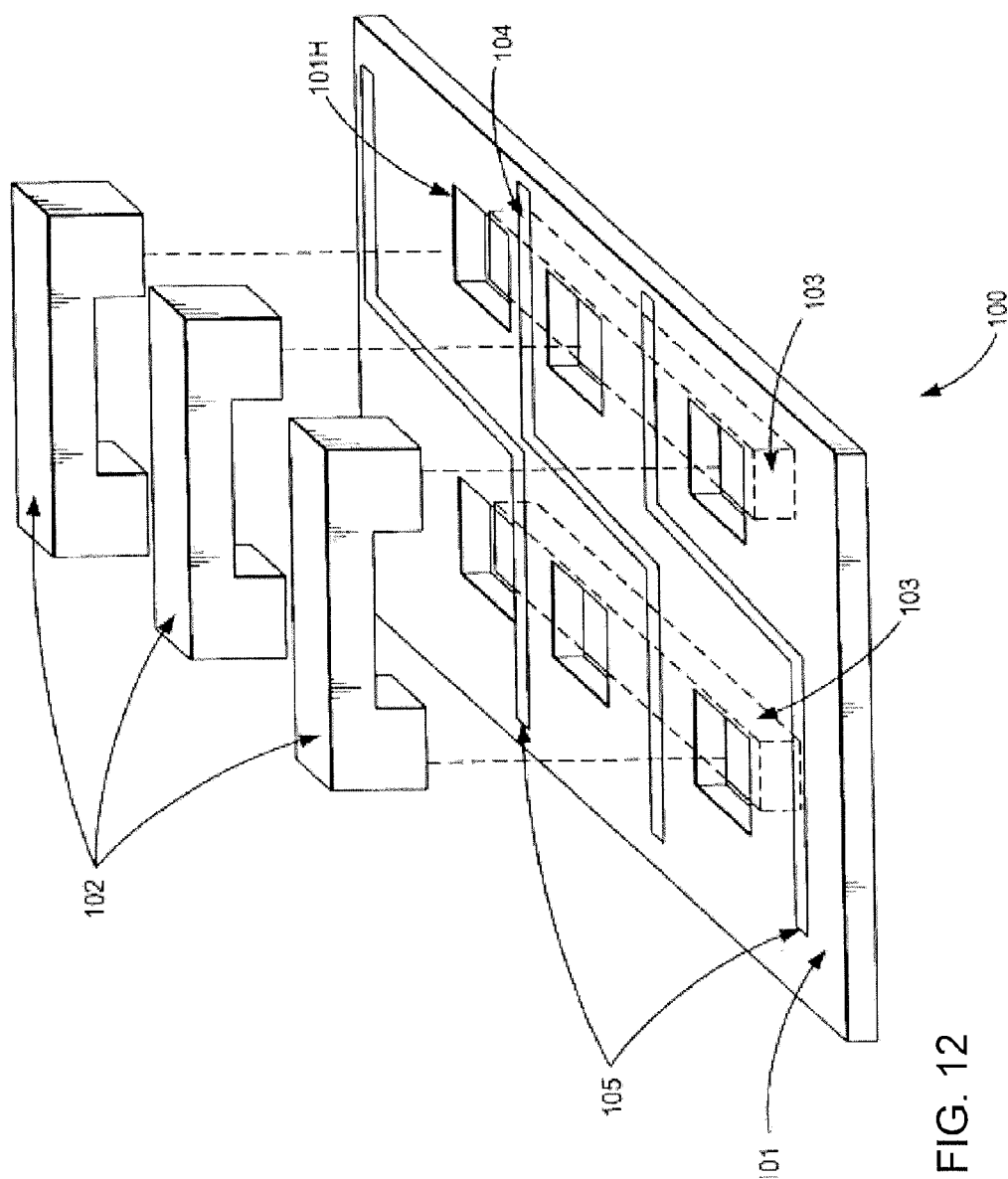
FIG. 11

U.S. Patent

Apr. 28, 2009

Sheet 9 of 13

US 7,525,408 B1



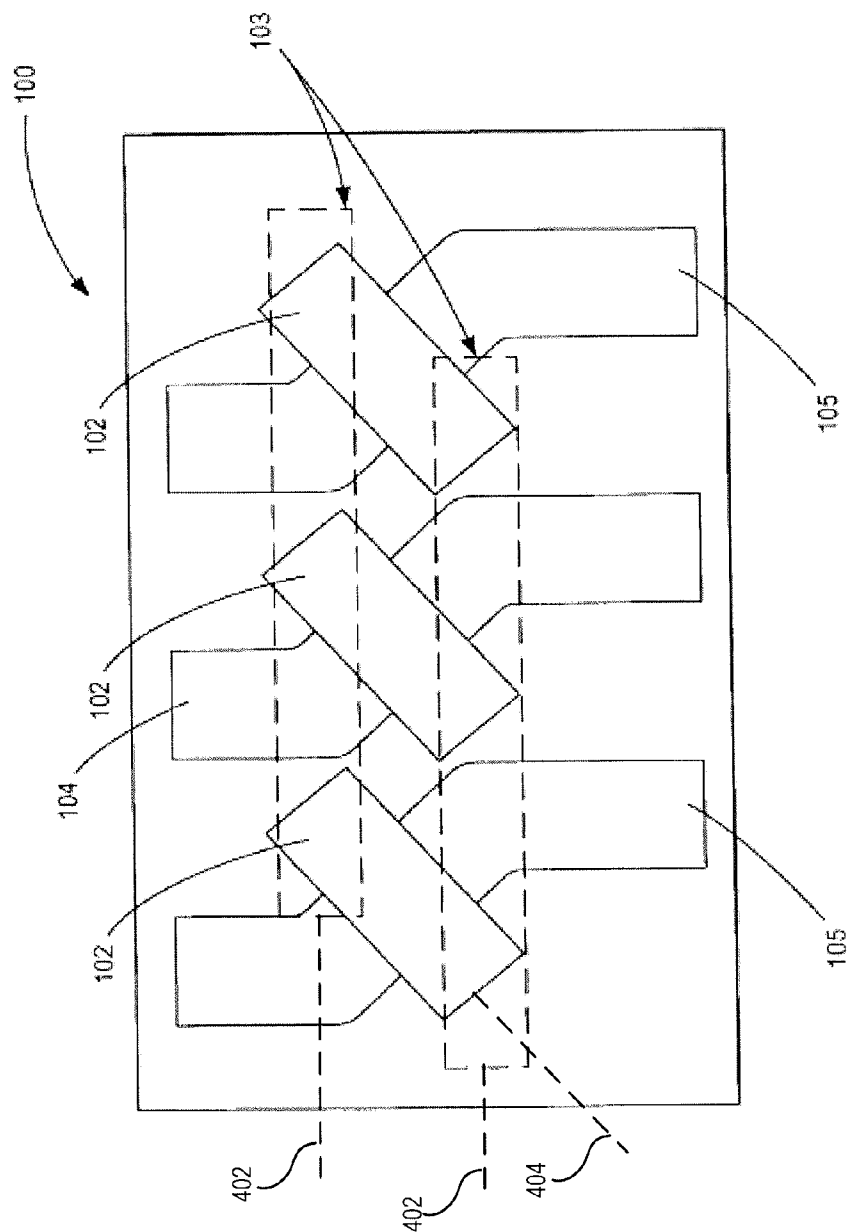


FIG. 13

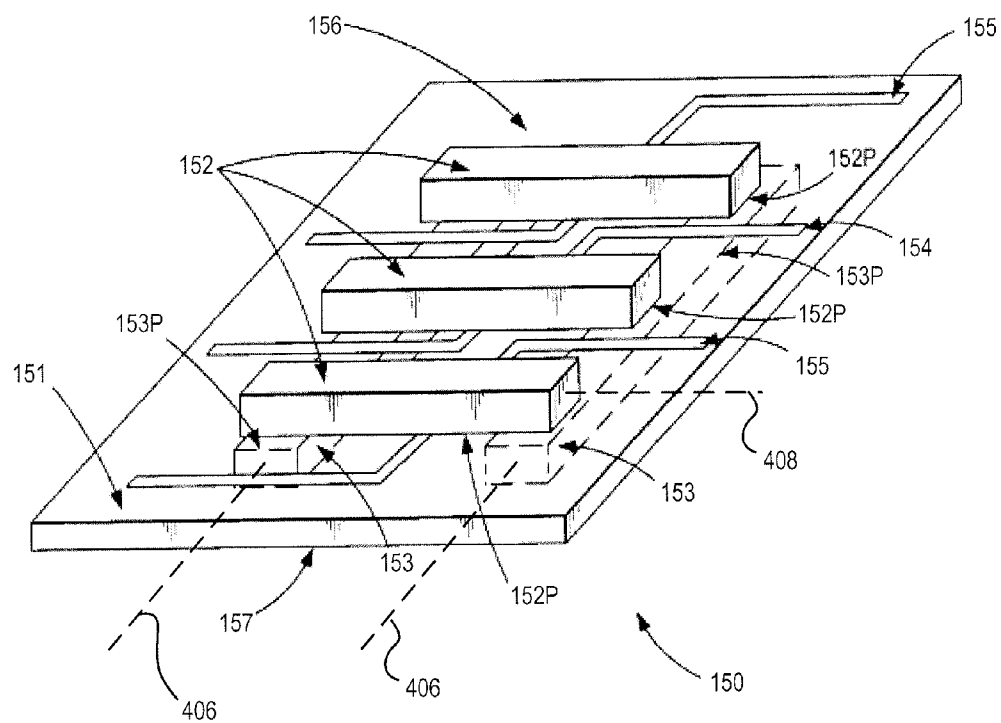


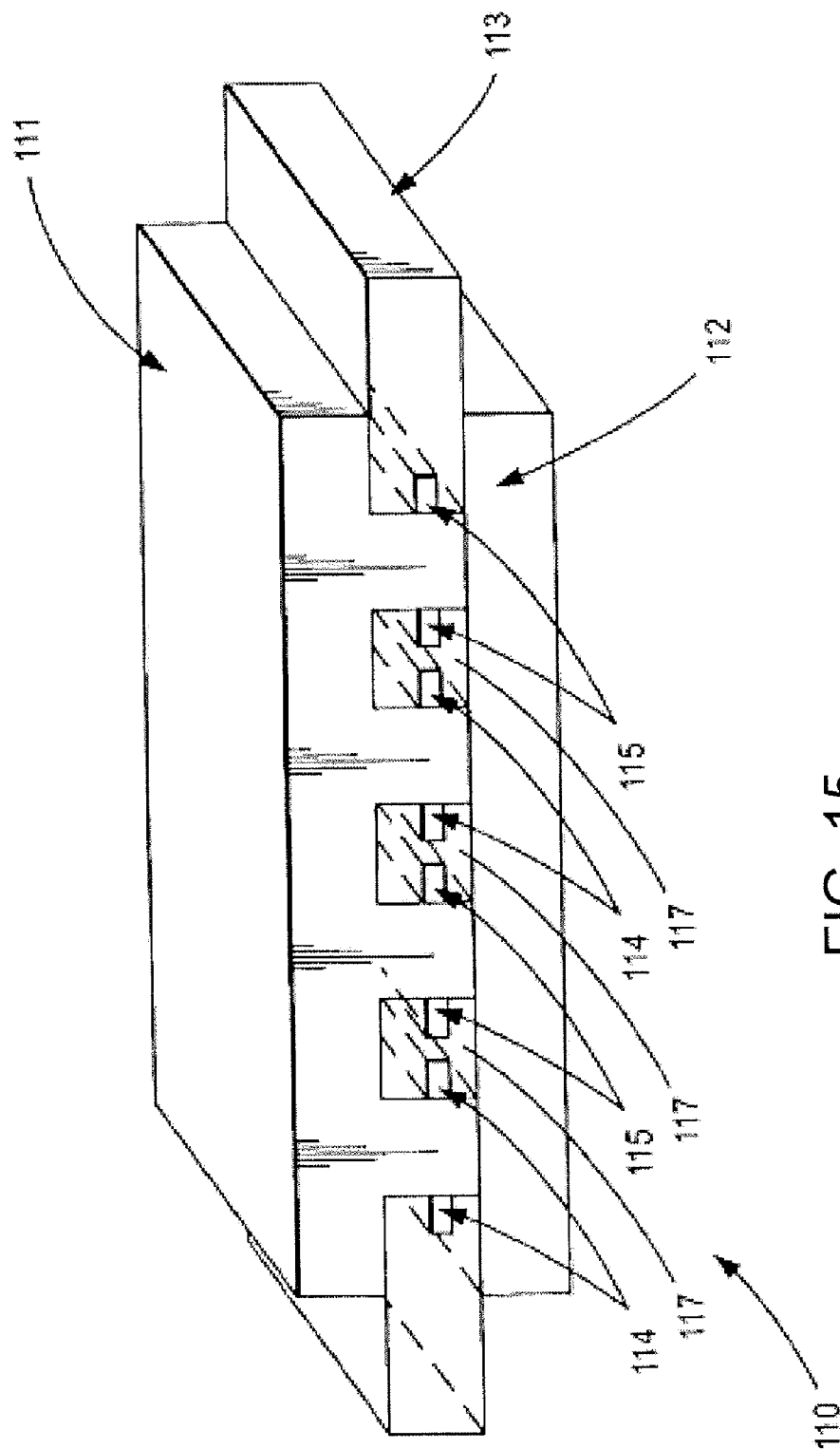
FIG. 14

U.S. Patent

Apr. 28, 2009

Sheet 12 of 13

US 7,525,408 B1



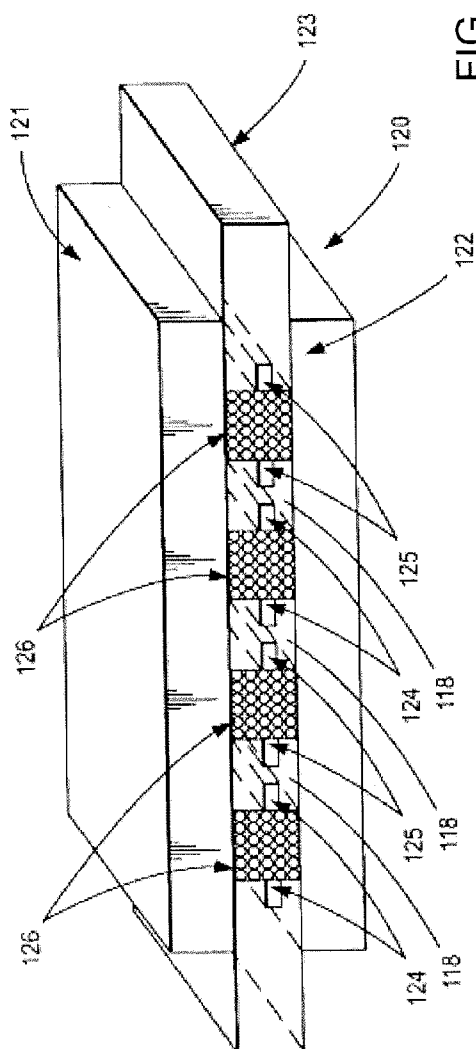


FIG. 16

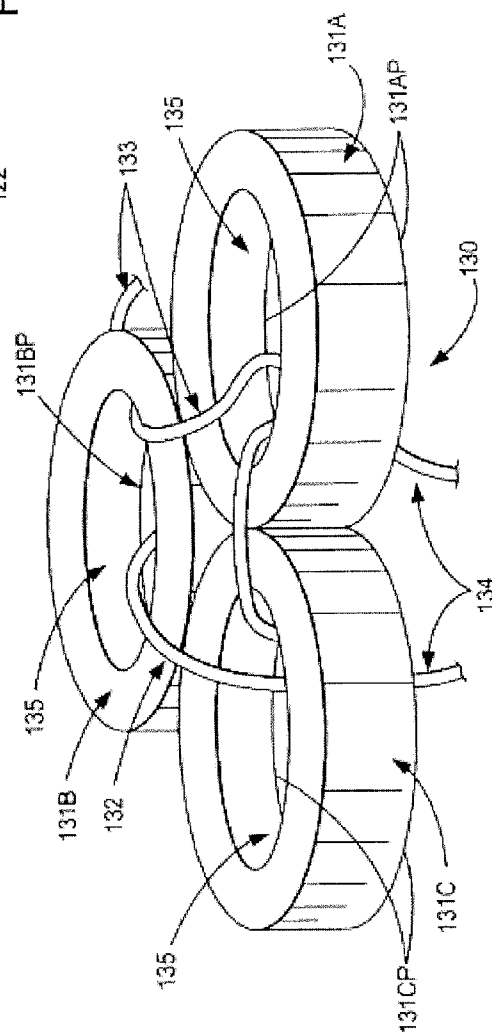


FIG. 17

US 7,525,408 B1

1

METHOD FOR MAKING MAGNETIC COMPONENTS WITH N-PHASE COUPLING, AND RELATED INDUCTOR STRUCTURES

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a divisional of U.S. patent application Ser. No. 10/318,896, filed 13 Dec. 2002, which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates generally to making DC-to-DC converters. More specifically the invention relates to construction of a coupled inductor within a multi-phase DC-to-DC converter.

2. Background of the Invention

A DC-to-DC converter, as known in the art, provides an output voltage that is a step-up, a step-down, or a polarity reversal of the input voltage source. Certain known DC-to-DC converters have parallel power units with inputs coupled to a common DC voltage source and outputs coupled to a load, such as a microprocessor. Multiple power-units can sometimes reduce cost by lowering the power and size rating of components. A further benefit is that multiple power units provide smaller per-power-unit peak current levels, combined with smaller passive components.

The prior art also includes switching techniques in parallel-power-unit DC-to-DC converters. By way of example, power units may be switched with pulse width modulation (PWM) or with pulse frequency modulation (PFM). Typically, in a parallel-unit buck converter, the energizing and de-energizing of the inductance in each power unit occurs out of phase with switches coupled to the input, inductor and ground. Additional performance benefits are provided when the switches of one power unit, coupling the inductors to the DC input voltage or to ground, are out of phase with respect to the switches in another power unit. Such a "multi-phase," parallel power unit technique results in ripple current cancellation at a capacitor, to which all the inductors are coupled at their respective output terminals.

It is clear that smaller inductances are needed in DC-to-DC converters to support the response time required in load transients and without prohibitively costly output capacitance. More particularly, the capacitance requirements for systems with fast loads, and large inductors, may make it impossible to provide adequate capacitance configurations, in part due to the parasitic inductance generated by a large physical layout. But smaller inductors create other issues, such as the higher frequencies used in bounding the AC peak-to-peak current ripple within each power unit. Higher frequencies and smaller inductances enable shrinking of part size and weight. However, higher switching frequencies result in more heat dissipation and lower efficiency. In short, small inductance is good for transient response, but large inductance is good for AC current ripple reduction and efficiency.

The prior art has sought to reduce the current ripple in multiphase switching topologies by coupling inductors. For example, one system set forth in U.S. Pat. No. 5,204,809, incorporated herein by reference, couples two inductors in a dual-phase system driven by an H bridge to help reduce ripple current. In one article, *Investigating Coupling Inductors in the Interleaving QSW VRM*, IEEE APEC (Wong, February 2000), slight benefit is shown in ripple reduction by coupling two windings using presently available magnetic core shapes.

2

However, the benefit from this method is limited in that it only offers slight reduction in ripple at some duty cycles for limited amounts of coupling.

One known DC-to-DC converter offers improved ripple reduction that either reduces or eliminates the aforementioned difficulties. Such a DC-to-DC converter is described in commonly owned U.S. Pat. No. 6,362,986 issued to Schultz et al., incorporated herein by reference. The '986 patent can improve converter efficiency and reduce the cost of manufacturing DC-to-DC converters.

Specifically, the '986 patent shows one system that reduces the ripple of the inductor current in a two-phase coupled inductor within a DC-to-DC buck converter. The '986 patent also provides a multi-phase transformer model to illustrate the working principles of multi-phase coupled inductors. It is a continuing problem to address scalability and implementation issues DC-to-DC converters.

As circuit components and, thus, printed circuit boards (PCB), become smaller due to technology advancements, smaller and more scalable DC-to-DC converters are needed to provide for a variety of voltage conversion needs. One specific feature presented hereinafter is to provide a DC-to-DC converter, the DC-to-DC converter being scalable in some embodiments. Another feature is to provide a converter that is mountable to a PCB. Yet another feature is to provide a lower cost manufacturing methodology for DC-to-DC converters, as compared to the prior art. These and other features will be apparent in the description that follows.

SUMMARY OF THE INVENTION

As used herein, a "coupled" inductor implies an interaction between multiple inductors of different phases. Coupled inductors described herein may be used within DC-to-DC converters or within a power converter for power conversion applications, for example.

A method of one aspect provides for constructing a magnetic core. Such a core is, for example, useful in applications detailed in the '986 patent. In one aspect, the method provides for constructing N-phase coupled inductors as both single and scalable magnetic structures, where N is greater than 1. An N-phase inductor as described herein may include N-number of windings. One method additionally describes construction of a magnetic core that enhances the benefits of using the scalable N-phase coupled inductor.

In one aspect, the N-phase coupled inductor is formed by coupling first and second magnetic cores in such a way that a planar surface of the first core is substantially aligned with a planar surface of the second core in a common plane. The first and second magnetic cores may be formed into shapes that, when coupled together, may form a single scalable magnetic core having desirable characteristics, such as ripple current reduction and ease of implementation. In one example, the cores are fashioned into shapes, such as a U-shape, an I-shape (e.g., a bar), an H-shape, a ring-shape, a rectangular-shape, or a comb. In another example, the cores could be fashioned into a printed circuit trace within a PCB.

In another aspect, certain cores form passageways through which conductive windings are wound when coupled together. Other cores may already form these passageways (e.g., the ring-shaped core and the rectangularly shaped core). For example, two H-shaped magnetic cores may be coupled at the legs of each magnetic core to form a passageway. As another example, a multi-leg core may be formed as a comb-shaped core coupled to an I-shaped core. In yet another example, two I-shaped cores are layered about a PCB such that passageways are formed when the two cores are coupled

US 7,525,408 B1

3

to one another at two or more places, or when pre-configured holes in the PCB are filled with a ferromagnetic powder.

Advantages of the method and structures herein include a scalable and cost effective DC-to-DC converter that reduces or nearly eliminates ripple current. The methods and structures further techniques that achieve the benefit of various performance characteristics with a single, scalable, topology.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows one multi-phase DC-to-DC converter system;

FIG. 2 shows one two-phase coupled inductor;

FIG. 3 shows one two-phase coupled ring-core inductor;

FIG. 4 shows one vertically mounted two-phase coupled inductor;

FIG. 5 shows one plate structured two-phase coupled inductor;

FIG. 6 shows one scalable multi-phase coupled inductor with H-shaped cores;

FIG. 7 shows one scalable multi-phase coupled inductor with rectangular-shaped cores;

FIG. 8 shows one scalable multi-phase coupled inductor with U-shaped cores;

FIG. 9 shows one integrated multi-phase coupled inductor with a comb-shaped core;

FIG. 10 shows one scalable multi-phase coupled inductor with combinations of shaped cores;

FIG. 11 shows one scalable multi-phase coupled inductor with "staple" cores;

FIG. 12 shows an assembly view of the coupled inductor of FIG. 11;

FIG. 13 shows a surface view of the inductor of FIG. 11;

FIG. 14 shows one scaleable coupled inductor with bar magnet cores;

FIG. 15 shows one multi-phase coupled inductor with through-board integration;

FIG. 16 shows another multi-phase coupled inductor with through-board integration; and

FIG. 17 shows one scalable multi-phase coupled ring-core inductor.

DETAILED DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a multi-phase DC-to-DC converter system 10. System 10 includes a power source 12 electrically coupled with N switches 14 and N inductors 24, with N=2, for supplying power to a load 16. Each switch and inductor pair 14, 24 represent one phase 26 of system 10, as shown. Inductors 24 cooperate together as a coupled inductor 28. Power source 12 may, for example, be either a DC power source, such as a battery, or an AC power source cooperatively coupled to a rectifier, such as a bridge rectifier, to provide DC power in signal 18. Each switch 14 may include a plurality of switches to perform the functions of DC-to-DC converter system 10.

In operation, DC-to-DC converter system 10 converts an input signal 18 from source 12 to an output signal 30. The voltage of signal 30 may be controlled through operation of switches 14, to be equal to or different from signal 18. Specifically, coupled inductor 28 has one or more windings (not shown) that extend through and about inductors 24, as described in detail below. These windings attach to switches 14, which collectively operate to regulate the output voltage of signal 30 by sequentially switching inductors 24 to signal 18.

4

When N=2, system 10 may for example be used as a two-phase power converter, (e.g., power supply). System 10 may also be used in both DC and AC based power supplies to replace a plurality of individual discrete inductors such that coupled inductor 28 reduces inductor ripple current, filter capacitances, and/or PCB footprint sizes, while delivering higher system efficiency and enhanced system reliability. Other functional and operational aspects of DC-to-DC converter system 10 may be exemplarily described in the '986 patent, features of coupled inductor 28 are described in detail below in connection with FIG. 2-FIG. 17. Those skilled in the art appreciate that system 10 may be arranged with different topologies to provide a coupled inductor 28 and without departing from the scope hereof.

FIG. 2 shows a two-phase coupled inductor 33, in accord with one embodiment. Inductor 33 may, for example, serve as inductor 28 of FIG. 1, with N=2. The two-phase coupled inductor 33 may include a first magnetic core 36A and a second magnetic core 36B. The first and second magnetic cores 36A, 36B, respectively, are coupled together such that planar surfaces 37A, 37B, respectively, of each core are substantially aligned in a common plane, represented by line 35. When the two magnetic cores 36A and 36B are coupled together, they cooperatively form a single magnetic core for use as a two-phase coupled inductor 33.

In this embodiment, the first magnetic core 36A may be formed from a ferromagnetic material into a U-shape. The second magnetic core 36B may be formed from the same ferromagnetic material into a bar, or I-shape, as shown. As the two magnetic cores 36A, 36B are coupled together, they form a passageway 38 through which windings 34A, 34B are wound. The windings 34A, 34B may be formed of a conductive material, such as copper, that wind though and about the passageway 38 and the magnetic core 36B. Moreover, those skilled in art should appreciate that windings 34A, 34B may include a same or differing number of turns about the magnetic core 36B. Windings 34A, 34B are shown as single turn windings, to decrease resistance through inductor 33.

The windings 34A and 34B of inductor 33 may be wound in the same or different orientation from one another. The windings 34A and 34B may also be either wound about the single magnetic core in the same number of turns or in a different number of turns. The number of turns and orientation of each winding may be selected so as to support the functionality of the '986 patent, for example. By orienting the windings 34A and 34B in the same direction, the coupling is directed so as to reduce the ripple current flowing in windings 34A, 34B.

Those skilled in the art should appreciate that a gap (not shown) may exist between magnetic cores 36A, 36B, for example to reduce the sensitivity to direct current when inductor 33 is used within a switching power converter. Such a gap is for example illustratively discussed as dimension A, FIG. 5.

The dimensional distance between windings 34A, 34B may also be adjusted to adjust leakage inductance. Such a dimension is illustratively discussed as dimension E, FIG. 5.

As shown, magnetic core 36A is a "U-shaped" core while magnetic core 36B is an unshaped flat plate. Those skilled in the art should also appreciate that coupled inductor 33 may be formed with magnetic cores with different shapes. By way of example, two "L-shaped" or two "U-shaped" cores may be coupled together to provide like overall form as combined cores 36A, 36B, to provide like functionality within a switching power converter. Cores 36A, 36B may be similarly replaced with a solid magnetic core block with a hole therein to form passageway 38. At least part of passageway 38 is free

US 7,525,408 B1

5

from intervening magnetic structure between windings 34A, 34B; air or non-magnetic structure may for example fill the space of passageway 38 and between the windings 34A, 34B. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings 34A, 34B, and within passageway 38; by way of example, the cross-sectional area of passageway 38 may be defined by the plane of dimensions 39A (depth), 39B (height), which is perpendicular to a line 39C (separation distance) between windings 34A, 34B.

FIG. 2 also illustrates one advantageous feature associated with windings 34A, 34B. Specifically, each of windings 34A, 34B is shown with a rectangular cross-section that, when folded underneath core 36B, as shown, produces a tab for soldering to a PCB, and without the need for a separate item. Other windings discussed below may have similar beneficial features.

FIG. 2 also shows planar surfaces 302, 304, 308, and 314, legs or sides 310 and 312, and width 300.

FIG. 3 shows a single two-phase ring-core coupled inductor 43, in accord with one embodiment. Inductor 43 may be combined with other embodiments herein, for example, to serve as inductor 28 of FIG. 1. The ring-core inductor 43 is formed from a ring magnetic core 44. The core 44 has a passageway 45; windings 40 and 42 are wound through passageway 45 and about the core 44, as shown. In this embodiment, core 44 is formed as a single magnetic core; however multiple magnetic cores, such as two semi-circles, may be cooperatively combined to form a similar core structure. Other single magnetic core embodiments shown herein may also be formed by cooperatively combining multiple magnetic cores as discussed in FIG. 17. Such a combination may align plane 44P of magnetic core 44 in the same plane of other magnetic cores 44, for example to facilitate mounting to a PCB. At least part of passageway 45 is free from intervening magnetic structure between windings 40, 42; air may for example fill the space of passageway 45 and between windings 40, 42. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings 40, 42, and within passageway 45.

In one embodiment, windings 40, 42 wind through passageway 45 and around ring magnetic core 44 such that ring magnetic core 44 and windings 40, 42 cooperate with two phase coupling within a switching power converter. Winding 40 is oriented such dc current in winding 40 flows in a first direction within passageway 45; winding 42 is oriented such that dc current in winding 42 flows in a second direction within passageway 45, where the first direction is opposite to the second direction. Such a configuration avoids dc saturation of core 44, and effectively reduces ripple current. See U.S. Pat. No. 6,362,986.

FIG. 4 shows a vertically mounted two-phase coupled inductor 54, in accord with one embodiment. Inductor 54 may be combined and/or formed with other embodiments herein, for example, to serve as inductor 28 of FIG. 1. The inductor 54 is formed as a rectangular-shaped magnetic core 55. The core 55 forms a passageway 56; windings 50 and 52 may be wound through passageway 56 and about the core 55. In this embodiment, the inductor 54 may be vertically mounted on a plane of PCB 57 (e.g., one end of passageway 56 faces the plane of the PCB 57) so as to minimize a "footprint", or real estate, occupied by the inductor 54 on the PCB 57. This embodiment may improve board layout convenience. Windings 50 and 52 may connect to printed traces 59A, 59B on the PCB 57 for receiving current. Additionally, windings 50 and 52 may be used to mount inductor 54 to the PCB 57, such as by flat portions 50P, 52P of respective windings 50, 52. Specifically, portions 50P,

6

52P may be soldered underneath to PCB 57. At least part of passageway 56 is free from intervening magnetic structure between windings 50, 52; air may for example fill the space of passageway 56 and between windings 50, 52. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings 50, 52, and within passageway 56; by way of example, the cross-sectional area of passageway 56 may be defined by the plane of dimensions 53A (height), 53B (depth), which is perpendicular to a line 53C (separation distance) between windings 50, 52. Also shown in FIG. 4 are widths 352 and 354, legs 356 and 358, planar surfaces 360, 362, 364, 366, 368, 372, and 374.

FIG. 4 further has advantages in that one winding 50 winds around one side of core 55, while winding 52 winds around another side of core 55, as shown. Such a configuration thus provides for input on one side of inductor 54 and output on the other side with convenient mating to a board layout of PCB 57.

FIG. 5 shows a two-phase coupled inductor 60, in accord with one embodiment. Inductor 60 may, for example, serve as inductor 28 of FIG. 1. The inductor 60 may be formed from first and second magnetic cores 61 and 62, respectively. The illustration of the cores 61 and 62 is exaggerated for the purpose of showing detail of inductor 60. The two cores 61 and 62 may be "sandwiched" about the windings 64 and 63. The dimensions E, C and A, in this embodiment, are part of the calculation that determines a leakage inductance for inductor 60. The dimensions of D, C, and A, combined with the thickness of the first and second cores 61 and 62, are part of the calculation that determines a magnetizing inductance of the inductor 60. For example, assuming dimension D is much greater than E, the equations for leakage inductance and magnetizing inductance can be approximated as:

$$L_1 = \frac{\mu_0 * E * C}{2 * A} \text{ and} \quad (1)$$

$$L_m = \mu_0 * D * C / (4 * A) \quad (2)$$

where μ_0 is the permeability of free space, L_1 is leakage inductance, and L_m is magnetizing inductance. One advantage of this embodiment is apparent in the ability to vary the leakage and the magnetizing inductances by varying the dimensions of inductor 60. For example, the leakage inductance and the magnetizing inductance can be controllably varied by varying the dimension E (e.g., the distance between the windings 64 and 63). In one embodiment, the cores 61 and 62 may be formed as conductive prints, or traces, directly with a PCB, thereby simplifying assembly processes of circuit construction such that windings 63, 64 are also PCB traces that couple through one or more planes of a multi-plane PCB. In one embodiment, the two-phase inductor 60 may be implemented on a PCB as two parallel thin-film magnetic cores 61 and 62. In another embodiment, inductor 60 may form planar surfaces 63P and 64P of respective windings 63, 64 to facilitate mounting of inductor 60 onto the PCB. Dimensions E, A between windings 63, 64 may define a passageway through inductor 60. At least part of this passageway is free from intervening magnetic structure between windings 63, 64; air may for example fill the space of the passageway and between windings 63, 64. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings 63, 64, and within the passageway; by way of example, the cross-sectional area of the passageway

US 7,525,408 B1

7

may be defined by the plane of dimensions A, C, which is perpendicular to a line parallel to dimension E between windings 63, 64.

FIG. 6 shows a scalable, multi-phase coupled inductor 70 that may be formed from a plurality of H-shaped magnetic cores 74, in accord with one embodiment. Inductor 70 may, for example, serve as inductor 28 of FIG. 1. The inductor 70 may be formed by coupling “legs” 74A of each H-shaped core 74 together. Each core 74 has one winding 72. The windings 72 may be wound through the passageways 71 formed by legs 74A of each core 74. The winding of each core 74 may be wound prior to coupling the several cores together such that manufacturing of inductor 70 is simplified. By way of example, cores 74 may be made and used later; if a design requires additional phases, more of the cores 74 may be coupled together “as needed” without having to form additional windings 72. Each core 74 may be mounted on a PCB, such as PCB 57 of FIG. 4, and be coupled together to implement a particular design. One advantage to inductor 70 is that a plurality of cores 74 may be coupled together to make a multi-core inductor that is scalable. In one embodiment, H-shaped cores 74 cooperatively form a four-phase coupled inductor. Other embodiments may, for example, scale the number of phases of the inductor 70 by coupling more H-shaped cores 74. For example, the coupling of another H-shaped core 74 may increase the number of phases of the inductor 70 to five. In one embodiment, the center posts 74C about which the windings 72 are wound may be thinner (along direction D) than the legs 74A (along direction D). Thinner center posts 74C may reduce winding resistance and increase leakage inductance without increasing the footprint size of the coupled inductor 70. Each of the H-shaped cores 74 has a planar surface 74P, for example, that aligns with other H-shaped cores in the same plane and facilitates mounting of inductor 70 onto PCB 74S. At least part of one passageway 71, at any location along direction D within the one passageway, is free from intervening magnetic structure between windings 72; for example air may fill the three central passageways 71 of inductor 70 and between windings 72 in those three central passageways 71. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings 72, and within passageway 71.

FIG. 7 shows a scalable, multi-phase coupled inductor 75 formed from a plurality of U-shaped magnetic cores 78 and an equal number of I-shaped magnetic cores 79 (e.g., bars), in accord with one embodiment. Inductor 75 may, for example, serve as inductor 28 of FIG. 1. The U-shaped cores 78 coupled with the I-shaped cores 79 may form rectangular-shaped core cells 75A, 75B, 75C, and 75D, each of which is similar to the cell of FIG. 2, but for the winding placement. The inductor 75 may be formed by coupling each of the rectangular-shaped core cells 75A, 75B, 75C, and 75D together. The windings 76 and 77 may be wound through the passageways (labeled “APERTURE”) formed by the couplings of cores 78 with cores 79 and about core elements. Similar to FIG. 6, the windings 76 and 77 of each rectangular-shaped core cell may be made prior to coupling with other rectangular-shaped core cells 75A, 75B, 75C, and 75D such that manufacturing of inductor 75 is simplified; additional inductors 75, may thus, be implemented “as needed” in a design. One advantage to inductor 75 is that cells 75A, 75B, 75C, and 75D—and/or other like cells—may be coupled together to make inductor 75 scalable. In the illustrated embodiment of FIG. 7, rectangular-shaped cells 75A, 75B, 75C, and 75D cooperatively form a five-phase coupled inductor. Each of the I-shaped cores 79 has a planar surface 79P, for example, that aligns

8

with other I-shaped cores in the same plane and facilitates mounting of inductor 75 onto PCB 79S. At least part of the Apertures is free from intervening magnetic structure between windings 76, 77; air may for example fill the space of these passageways and between windings 76, 77. By way of example, each Aperture is shown with a pair of windings 76, 77 passing therethrough, with only air filling the space between the windings 76, 77. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings 76, 77, and within each respective Aperture.

FIG. 8 shows a scalable, multi-phase coupled inductor 80 formed from a plurality of U-shaped magnetic cores 81 (or C-shaped depending on the orientation), in accord with one embodiment. Each magnetic core 81 has two lateral members 81L and an upright member 81U, as shown. Inductor 80 may, for example, serve as inductor 28 of FIG. 1. The inductor 80 may be formed by coupling lateral members 81L of each U-shaped core 81 (except for the last core 81 in a row) together with the upright member 81U of a succeeding U-shaped core 81, as shown. The windings 82 and 83 may be wound through the passageways 84 formed between each pair of cores 81. Scalability and ease of manufacturing advantages are similar to those previously mentioned. For example, winding 82 and its respective core 81 may be identical to winding 83 and its respective core 81, forming a pair of like cells. More cells can be added to desired scalability. Each of the U-shaped cores 81 has a planar surface 81P, for example, that aligns with other U-shaped cores 81 in the same plane and facilitates mounting of inductor 80 onto PCB 81S. At least part of one passageway 84 is free from intervening magnetic structure between windings 82, 83; air may for example fill the space of this passageway 84 and between windings 82, 83. By way of example, three passageways 84 are shown each with a pair of windings 82, 83 passing therethrough, with only air filling the space between the windings 82, 83. One winding 82 is at the end of inductor 80 and does not pass through such a passageway 84; and another winding 83 is at another end of inductor 80 and does not pass through such a passageway 84. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings 82, 83, and within passageway 84.

FIG. 9 shows a multi-phase coupled inductor 85 formed from a comb-shaped magnetic core 86 and an I-shaped (e.g., a bar) magnetic core 87, in accord with one embodiment. Inductor 85 may, for example, serve as inductor 28 of FIG. 1. The inductor 85 may be formed by coupling a planar surface 86P of “teeth” 86A of the comb-shaped core 86 to a planar surface 87P of the I-shaped core 87 in substantially the same plane. The windings 88 and 89 may be wound through the passageways 86B formed by adjacent teeth 86A of comb-shaped core 86 as coupled with I-shaped core 87. The windings 88 and 89 may be wound about the teeth 86A of the comb-shaped core 86. FIG. 9 also shows end passageways 200, planar surfaces 202, 204, 206, 208, 210, 212, 214, and 224, height 216, depth 218, and widths 220 and 222. This embodiment may also be scalable by coupling inductor 85 with other inductor structures shown herein. For example, the U-shaped magnetic cores 81 of FIG. 8 may be coupled to inductor 85 to form a multi-phase inductor, or a N+1 phase inductor. The I-shaped core 87 has a planar surface 87P, for example, that facilitates mounting of inductor 85 onto PCB 87S. At least part of one passageway 86B is free from intervening magnetic structure between windings 88, 89; air may for example fill the space of this passageway 86B and between windings 88, 89. By way of example, three passageways 86B are shown each with a pair of windings 88, 89

US 7,525,408 B1

9

passing therethrough, with only air filling the space between the windings **88**, **89**. One winding **88** is at the end of inductor **85** and does not pass through such a passageway **86B**; and another winding **89** is at another end of inductor **85** and does not pass through such a passageway **86B**. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **88**, **89**, and within passageway **86B**.

In one embodiment, windings **88**, **89** wind around teeth **86A** of core **86**, rather than around I-shaped core **87** or the non-teeth portion of core **86**.

FIG. **10** shows a scalable, multi-phase coupled inductor **90** that may be formed from a comb-shaped magnetic core **92** and an I-shaped (e.g., a bar) magnetic core **93**, in accord with one embodiment. Inductor **90** may, for example, serve as inductor **28** of FIG. **1**. The inductor **90** may be formed by coupling “teeth” **92A** of the comb-shaped core **92** to the I-shaped core **93**, similar to FIG. **8**. The inductor **90** may be scaled to include more phases by the addition of the one more core cells to form a scalable structure. In one embodiment, H-shaped cores **91** (such as those shown in FIG. **6** as H-shaped magnetic cores **74**), may be coupled to cores **92** and **93**, as shown. The windings **94** and **95** may be wound through the passageways **90A** formed by the teeth **92A** as coupled with I-shaped core **93**. The windings **94** and **95** may be wound about the teeth **92A** of core **92** and the “bars” **91A** of H-shaped cores **91**. Scalability and ease of manufacturing advantages are similar to those previously mentioned. Those skilled in the art should appreciate that other shapes, such as the U-shaped cores and rectangular shaped cores, may be formed similarly to cores **92** and **93**. Each of the I-shaped core **92** and the H-shaped cores **91** has a respective planar surface **92P** and **91P**, for example, that aligns in the same plane and facilitates mounting of inductor **90** onto PCB **90S**. At least part of one passageway **90A** is free from intervening magnetic structure between windings **94**, **95**; air may for example fill the space of this passageway **90A** and between windings **94**, **95**. By way of example, five passageways **90A** are shown each with a pair of windings **94**, **95** passing therethrough, with only air filling the space between the windings **94**, **95**. One winding **94** is at the end of inductor **90** and does not pass through such a passageway **90A**; and another winding **95** is at another end of inductor **90** and does not pass through such a passageway **90A**. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings **94**, **95**, and within passageway **90A**.

FIGS. **11-13** show staple magnetic cores **102** that may serve to implement a scalable multi-phase coupled inductor **100**. Inductor **100** may, for example, serve as inductor **28** of FIG. **1**. The staple magnetic cores **102** are, for example, U-shaped and may function similar to a “staple”. The staple magnetic cores **102** may connect, or staple, through PCB **101** to bus bars **103** to form a plurality of magnetic core cells. For example, the two bus bars **103** may be affixed to one side of PCB **101** such that the staple magnetic cores **102** traverse through the PCB **101** from the opposite side of the PCB (e.g., via apertures **101H**) to physically couple to the bus bars **103**. One staple magnetic core may implement a single phase for the inductor **100**; thus the inductor **100** may be scalable by adding more of staple magnetic cores **102** and windings **104**, **105**. For example, a two-phase coupled inductor would have two staple magnetic cores **102** coupled to bus bars **103** with each core having a winding, such as windings **104**, **105**; the number of phases are thus equal to the number of staple magnetic cores **102** and windings **104**, **105**. By way of example, inductor **100**, FIG. **11**, shows a 3-phase inductor.

10

Bus bars **103** may have center axes **402** and staple magnetic cores **102** may have center axes **404**.

Advantages of this embodiment provide a PCB structure that may be designed in layout. As such, PCB real estate determinations may be made with fewer restrictions, as the inductor **100** becomes part of the PCB design. Other advantages of the embodiment are apparent in FIG. **13**. There, it can be seen that the staples **102** may connect to PCB **101** at angles to each PCB trace (i.e., windings **104** and **105**) so as to not incur added resistance while at the same time improving adjustability of leakage inductance. For example, extreme angles, such as 90 degrees, may increase the overall length of a PCB trace, which in turn increases resistance due to greater current travel. Further advantages of this embodiment include the reduction or avoidance of solder joints, which can significantly diminish high current. Additionally, the embodiment may incur fewer or no additional winding costs as the windings are part of the PCB; this may improve dimensional control so as to provide consistent characteristics such as AC resistance and leakage inductance.

Similar to coupled inductor **100**, FIG. **14** shows bar magnetic cores **152**, **153** that serve to implement a scalable coupled inductor **150**. Inductor **150** may, for example, serve as inductor **28** of FIG. **1**. The bar magnetic cores **152**, **153** are, for example, respectively mounted to opposing sides **156**, **157** of PCB **151**. Each of the bar magnetic cores **152**, **153** has, for example, a respective planar surface **152P**, **153P** that facilitates mounting of the bar magnetic cores to PCB **151**. The bar magnetic cores **152**, **153**, in this embodiment, do not physically connect to each other but rather affix to the sides of **156**, **157** such that coupling of the inductor **150** is weaker. The coupling of the inductor **150** may, thus, be determinant upon the thickness of the PCB **151**; this thickness forms a gap between cores **152** and **153**. One example of a PCB that would be useful in such an implementation is a thin polyimide PCB. One bar magnetic core **152** or **153** may implement a single phase for the inductor **150**; and inductor **150** may be scalable by adding additional bar magnetic cores **152** or **153**. For example, a two-phase coupled inductor has two bar magnetic cores **152** coupled to two bus bars **153**, each core having a winding **154** or **155** respectively. The number of phases are therefore equal to the number of bar magnetic cores **152**, **153** and windings **154**, **155**. One advantage of the embodiment of FIG. **14** is that no through-holes are required in PCB **151**. The gap between cores **152** and **153** slightly reduces coupling so as to make the DC-to-DC converter system using coupled inductor **150** more tolerant to DC current mismatch. Another advantage is that all the cores **152**, **153** are simple, inexpensive I-shaped magnetic bars. Cores **152** may have center axes **408**, and cores **153** may have center axes **406**.

FIGS. **15-16** each show a multi-phase coupled inductor (e.g., **110** and **120**, respectively) with through-board integration, in accord with other embodiments. FIG. **15** shows a coupled inductor **110** that may be formed from a comb-shaped core **111** coupled to an I-shaped core **112** (e.g., a bar), similar to that shown in FIG. **9**. In this embodiment, the cores **111** and **112** may be coupled through PCB **113** and are integrated with PCB **113**. The windings **114**, **115** may be formed in PCB **113** and/or as printed circuit traces on PCB **113**, or as wires connected thereto.

In FIG. **15**, comb-shaped core **111** and I-shaped core **112** form a series of passageways **117** within coupled inductor **110**. At least part of one passageway **117** is free from intervening structure between windings **114**, **115**; air may for example fill the space of this passageway **117** and between windings **114**, **115**. By way of example, three passageways **117** are shown each with a pair of windings **114**, **115** passing

US 7,525,408 B1

11

therethrough, with non-magnetic structure of PCB 113 filling some or all of the space between the windings 114, 115. One winding 114 is at the end of inductor 110 and does not pass through such a passageway 117; and another winding 115 is at another end of inductor 110 and does not pass through such a passageway 117. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings 114, 115, and within passageway 117.

FIG. 16 shows another through-board integration in a coupled inductor 120. In this embodiment, magnetic cores 121 and 122 may be coupled together by “sandwiching” the cores 121, 122 about PCB 123. The connections to the cores 121, 122 may be implemented via holes 126 in the PCB 123. The holes 126 may be filled with a ferromagnetic powder and/or bar that couples the two cores together, when sandwiched with the PCB 123. Similarly, the windings 124, 125 may be formed in PCB 123 and/or as printed circuit traces on PCB 123, or as wires connected thereto. Inductors 110 and 120 may, for example, serve as inductor 28 of FIG. 1. In this embodiment, the windings 114 and 115 are illustrated as PCB traces located within a center, or interior, plane of the PCB 123. Those skilled in the art should readily appreciate that the windings 114 and 115 may be embedded into any layer of the PCB and/or in multiple layers of the PCB, such as exterior and/or interior layers of the PCB.

In FIG. 16, cores 121 and 122 and ferromagnetic-filled holes 126 form a series of passageways 118 within coupled inductor 120. At least part of one passageway 118 is free from intervening structure between windings 124, 125; air may for example fill the space of this passageway 118 and between windings 124, 125. By way of example, three passageways 118 are shown each with a pair of windings 124, 125 passing therethrough, with non-magnetic structure of PCB 123 filling some or all of the space between the windings 124, 125. One winding 124 is at the end of inductor 120 and does not pass through such a passageway 118; and another winding 125 is at another end of inductor 120 and does not pass through such a passageway 118. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between windings 124, 125, and within passageway 118.

FIG. 17 shows a multi-phase scalable coupled ring-core inductor 130, in accord with one embodiment. The inductor 130 may be formed from multiple ring magnetic cores 131A, 131B, and 131C. In this embodiment, cores 131A, 131B, and 131C may be coupled to one another. The ring magnetic cores 131A, 131B, and 131C may have respective planar surfaces 131AP, 131BP, and 131CP, for example, that align in the same plane, to facilitate mounting with electronics such as a PCB. Each core may have an passageway 135 through which windings 132, 133, and 134 may be wound. As one example, cores 131A and 131B may be coupled to one another as winding 133 may be wound through the passageways 135 of those two cores. Cores 131C and 131A may be coupled to one another as winding 134 is wound through the passageways of those two cores. In another embodiment, the multiple ring magnetic cores 131A, 131B, and 131C may be coupled together by windings such that inductor 130 appears as a string or a chain. In one embodiment, intervening magnetic structure fills no more than 50% of a cross-sectional area between the windings within each respective passageway 135.

While some inductor embodiments include two-phase coupling, such as those shown in FIGS. 2-5, it is not intended that inductor coupling should be limited to two-phases. For example, a coupled inductor with two windings would func-

12

tion as a two-phase coupled inductor with good coupling, but coupling additional inductors together may advantageously increase the number of phases as a matter of design choice. Integration of multiple inductors that results in increased phases may achieve current ripple reduction of a power unit coupled thereto; examples of such are shown in FIGS. 6-8, 10, and 17. Coupling two or more two-phase inductor structures together to create a scalable N-phase coupled inductor may achieve an increased number of phases of an inductor. The windings of such an N-phase coupled inductor may be wound through the passageways and about the core such as those shown in FIGS. 6-8, 10, and 17.

Since certain changes may be made in the above methods and systems without departing from the scope hereof, one intention is that all matter contained in the above description or shown in the accompanying drawings be interpreted as illustrative and not in a limiting sense. By way of example, those skilled in the art should appreciate that items as shown in the embodiments may be constructed, connected, arranged, and/or combined in other formats without departing from the scope of the invention. Another intention includes an understanding that the following claims are to cover all generic and specific features of the invention described herein, and all statements of the scope of the invention which, as a matter of language, might be said to fall there between.

We claim:

1. An N-phase coupled inductor for magnetically coupling N phases of a power converter, comprising:

a magnetic core including a first and a second magnetic element and N connecting magnetic elements, N being an integer greater than one, the first and second magnetic elements being disposed parallel to each other and separated by a linear separation distance, each connecting magnetic element being coupled to the first and second magnetic elements; and

N windings, each of the N windings for electrically connecting to a respective phase of the power converter, each connecting magnetic element having a respective one of the N windings wound at least partially thereabout, two of the N windings being at least partially wound about a respective one of the N connecting magnetic elements and one of the first and second magnetic elements, and N-2 of the N windings being at least partially wound about a respective one of the N connecting magnetic elements and both of the first and second magnetic elements.

2. The coupled inductor of claim 1, each of the first and second magnetic elements having an I-shape.

3. The coupled inductor of claim 1, each of the connecting magnetic elements having a U-shape.

4. The coupled inductor of claim 1, each of the connecting magnetic elements having an I-shape.

5. The coupled inductor of claim 1, each connecting magnetic element being disposed such that a center axis of the connecting magnetic element is about orthogonal to a center axis of the first and second magnetic elements.

6. The coupled inductor of claim 1, each connecting magnetic element being disposed such that a center axis of the connecting magnetic element forms a first angle with respect to a center axis of the first magnetic element and a second angle with respect a center axis of the second magnetic element, the first and second angles being less than ninety degrees.

7. The coupled inductor of claim 1, each winding having rectangular cross section.

8. An N-phase coupled inductor for magnetically coupling N phases of a power converter, comprising:

US 7,525,408 B1

13

a printed circuit board for supporting the coupled inductor, the printed circuit board having a first side opposite a second side, the printed circuit board forming 2N apertures, N being an integer greater than one;

a magnetic core including a first and a second magnetic element and N connecting magnetic elements, the first and second magnetic elements being disposed parallel to each other on the first side of the printed circuit board, the first and second magnetic elements being separated by a linear separation distance along the first side of the printed circuit board, each connecting magnetic element being disposed on the second side of the printed circuit board and coupled to the first and second magnetic elements via two of the 2N apertures of the printed circuit board; and

N windings formed on the printed circuit board, each of the N windings for electrically connecting to a respective phase of the power converter, each connecting magnetic element having a respective one of the N windings wound at least partially thereabout, two of the N windings being at least partially wound about a respective one of the N connecting magnetic elements and one of the first and second magnetic elements, and N-2 of the N windings being at least partially wound about a respective one of the N connecting magnetic elements and both of the first and second magnetic elements.

9. The coupled inductor of claim 8, each of the first and second magnetic elements having an I-shape.

10. The coupled inductor of claim 8, each of the connecting magnetic elements having a U-shape.

11. The coupled inductor of claim 8, each connecting magnetic element being disposed such that a center axis of the connecting magnetic element is about orthogonal to a center axis of the first and second magnetic elements.

12. The coupled inductor of claim 8, each connecting magnetic element being disposed such that a center axis of the connecting magnetic element forms a first angle with respect to a center axis of the first magnetic element and a second angle with respect a center axis of the second magnetic element, the first and second angles being less than ninety degrees.

14

13. The coupled inductor of claim 8, each winding forming an angle in a plane of the printed circuit board, the angle being less than ninety degrees.

14. An N-phase coupled inductor for magnetically coupling N phases of a power converter, comprising:

a magnetic core including a first and a second magnetic element and N connecting magnetic elements, N being an integer greater than one, the first and second magnetic elements being disposed parallel to each other and separated by a linear separation distance, each connecting magnetic element being coupled to the first and second magnetic elements, the first and second magnetic elements and the N connecting elements cooperatively forming N-1 passageways; and

N windings, each of the N windings for electrically connecting to a respective phase of the power converter, each winding being wound about a respective connecting element and at least partially through at least one passageway, and

each passageway having two of the N windings wound at least partially therethrough.

15. The coupled inductor of claim 14, each of the first and second magnetic elements having an I-shape.

16. The coupled inductor of claim 14, each of the connecting magnetic elements having a U-shape.

17. The coupled inductor of claim 14, each of the connecting magnetic elements having an I-shape.

18. The coupled inductor of claim 14, each connecting magnetic element being disposed such that a center axis of the connecting magnetic element is about orthogonal to a center axis of the first and second magnetic elements.

19. The coupled inductor of claim 14, each connecting magnetic element being disposed such that a center axis of the connecting magnetic element forms a first angle with respect to a center axis of the first magnetic element and a second angle with respect a center axis of the second magnetic element, the first and second angles being less than ninety degrees.

20. The coupled inductor of claim 14, each winding having rectangular cross section.

* * * * *